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11 Wide Area Control of FACTS

FACTS-control has always to cope with speed and in the case of power flow control with exchange of system wide information. The high speed exchange of data to react on contingencies needs to be ensured to fulfill the requirements of the NISC-architecture according to the specifications in chapter 9. Online monitoring of the system status is needed for the optimization of the FACTS-device applications. Especially for power flow control and power system oscillations a dynamic performance evaluation supports an optimized transmission capability and an adaptive damping control.

Although pioneered already in the 80s, it is not until now phasor measurement units (PMU) have become widely available in power systems [1]. However, since recently wide-area measurement systems based on PMUs are becoming proven technology and are seen by many utilities as one of the most promising ways to gain more detailed information to operate the networks closer to the limits. Typically a wide-area measurement system based on phasor measurements provides access to system-wide data with a time resolution of tens of Hertz. The amount of gathered data becomes large, and the data need proper processing to be used either for the operator support or as part of the control system especially for FACTS. This chapter discusses wide area measurement and control systems as part of the coordinating FACTS-control.

11.1 Wide Area Monitoring and Control System

A wide-area measurement system (WAMS) can provide streaming measurements at update rates of 10-20 Hz, which enables monitoring not only of slow phenomena such as voltage and load evolution dynamics, but also faster phenomena such as oscillatory, transient and frequency dynamics. However, because of the high time-resolution of the measurements a WAMS will deliver huge amounts of data that need specific algorithms to use the provided information. The WAMS serves as the infrastructure necessary to implement wide-area stability control or system protection schemes [2].

Figure 11.1 shows the basic setup of a WAMS system. PMUs are placed within a critical area of the power system. This area could be for example a specific corridor. The PMUs are placed to derive a model of the specific area out of their measurements.

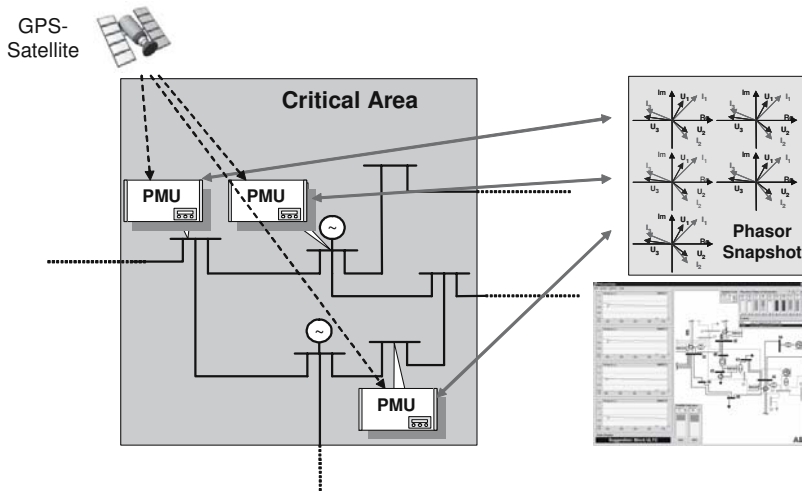


Fig. 11.1. Basic setup of a wide area measurement system

All PMUs are time-synchronized via a GPS-satellite time signal. Therefore the data from different PMUs can be directly compared which allows to directly measure voltage and current angles. The measured data are transmitted via communication channels to a central computer running the applications. Figure 11.2 shows the more detailed architecture of a WAMS system including the interfaces to SCADA/EMS and substation automation as well as the closed control loops back to network controllers like FACTS-devices.

The central computer contains services for preprocessing the incoming phasor measurements and basic services. The incoming measurement data must be sorted according to their time stamps and missing information must be detected. If the number of PMU data allows a full observability of the system a PMU based state estimation can be calculated. With PMUs in every second substation even topology detection can be performed. For most applications an estimation of a model of a specific area like a corridor is sufficient and limits the complexity of the WAMS.

An interface to the SCADA/EMS system allows receiving topology information and device parameters, like line inductance and the switching status. On the other hand, PMU information can be integrated into the conventional State Estimation to improve the accuracy. The Graphic User Interface (GUI) of the WAMS system can be kept separately or integrated into the SCADA/EMS screens.

The WAMS system runs various applications for wide area monitoring, control and protection. The monitoring performs for example stability assessments. Based on this information, control or protection actions, like the FACTS-control or for example load shedding schemes can be executed. The control signals are going back either directly to local controllers for specific devices or to substation automation systems.

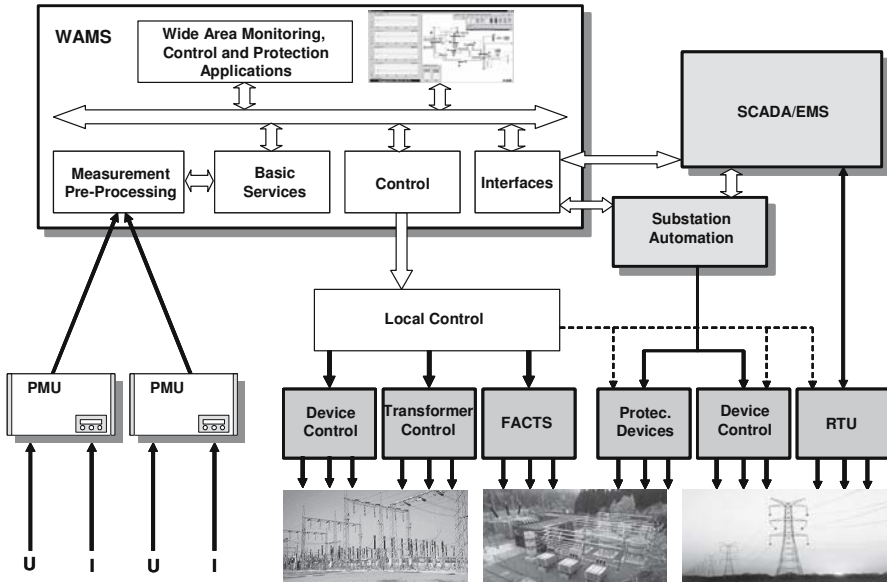


Fig. 11.2. Architecture of a wide area monitoring, control and protection system

The maximum performance of the applications in terms of speed is mainly limited by the communication channels. The data transmission from PMU to the central system and back to a device controller can be assumed to be between 50 and 200 ms for each direction.

In general a WAMS is structurally placed between SCADA/EMS and local control and protection systems. Figure 11.3 shows the basic characteristics.

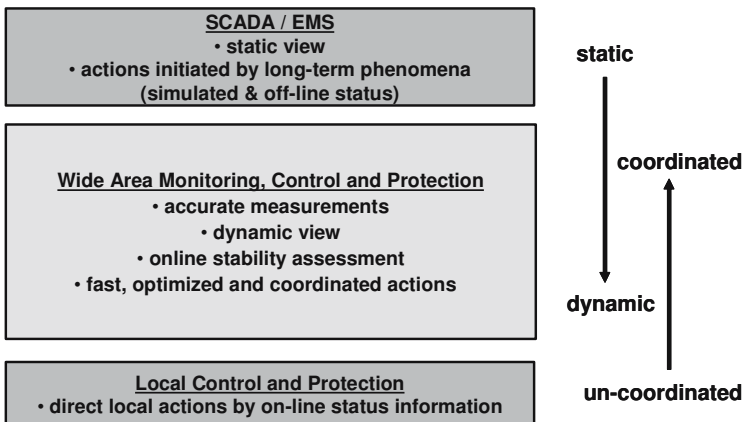


Fig. 11.3. Wide area monitoring, control and protection system capabilities in comparison to SCADA/EMS and local control and protection

11.2 Wide Area Monitoring Applications

Existing methods for using the PMU data are:

- Voltage stability monitoring for transmission corridors,
- thermal limit monitoring for transmission lines,
- oscillatory stability monitoring.

These methods can be used with PMUs placed in a few key locations only. Each application has its own requirements in terms of the number of required measurement points. However, often the same measurements can be used for more than one application. In a large-scale WAMS where a major part of the substations are equipped with PMUs, more advanced applications can be utilized, for example:

- State- and topology calculation providing dynamic snapshots of the power system,
- loadability calculation using OPF or other optimization techniques,
- post-contingency prediction of system state, especially for voltage stability.

These second applications are based on a completely observed network from which a detailed network model is derived.

11.2.1 Corridor Voltage Stability Monitoring

In real power systems main limitations are typically caused by transmission corridors between generation and load areas or for trading purposes between regions. If these transmission corridors extend a certain length, voltage stability is the limiting factor, which needs to be carefully supervised to utilize the corridor to a maximum extend.

The main principle of the corridor voltage stability monitoring is to use the measurements from both ends of a transmission corridor, reduce them to lump currents and voltages, and to compute a reduced equivalent model of the transmission corridor.

First we calculate the parameters of a T-equivalent of the actual transmission corridor, including any load or generation that may be present in the transmission corridor as shown in Figure 11.4.

This reduced model can then be used to analytically determine the theoretical maximum loading of the corridor and the margin to voltage instability. Optionally, load shedding can be activated based on the loadability estimate to avoid voltage collapse in the load region when the corridor loading becomes excessive. Since the method is based on a reduced equivalent network model, which is estimated on-line from the PMU measurements, no parameter input is required to estimate the stability limit.

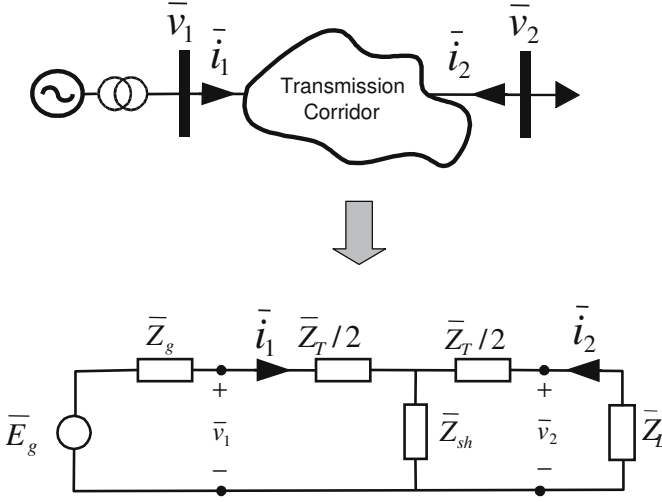


Fig. 11.4. T- and Thevenin-equivalents of a transmission corridor fed by a generation area

Applying Ohm's and Kirchoff's laws, with the known complex quantities (measured phasors) $\bar{v}_1$, $\bar{i}_1$, $\bar{v}_2$ and $\bar{i}_2$ we can calculate the complex impedances $\bar{Z}_T$, $\bar{Z}_{sh}$ and $\bar{Z}_L$ as follows

$$\bar{Z}_T = 2 \frac{\bar{v}_1 - \bar{v}_2}{\bar{i}_1 - \bar{i}_2} \quad (11.1)$$

$$\bar{Z}_{sh} = \frac{\bar{v}_1 \bar{i}_2 - \bar{v}_2 \bar{i}_1}{\bar{i}_1^2 - \bar{i}_2^2} \quad (11.2)$$

$$\bar{Z}_L = \frac{\bar{v}_2}{-\bar{i}_2} \quad (11.3)$$

The complex voltage $\bar{E}_g$ and impedance of the equivalent voltage source $\bar{Z}_g$ cannot be simultaneously calculated in the same straightforward way, so one of them must be assumed to be known to avoid the time delay of an estimation procedure like the one in [3] and [4]. If the generators have voltage controllers and can be assumed to stay within their capability limits, $\bar{E}_g$ can be assumed to be constant and $\bar{Z}_g$ could then be calculated using:

$$\bar{Z}_g = \frac{\bar{E}_g - \bar{v}_1}{\bar{i}_1} \quad (11.4)$$

However, in most practical cases it is more realistic to assume that $\bar{Z}_g$ is known since it typically comprises of the step-up transformers and short transmis-

sion lines to the beginning of the transmission corridor. It is therefore preferential to calculate the equivalent complex voltage of the generators as follows:

$$\bar{E}_g = \bar{v}_1 + \bar{Z}_g \bar{i}_1 \quad (11.5)$$

Once we have calculated the parameters of the T- and Thevenin equivalent, a second Thevenin equivalent for the combined generation and transmission corridor can be calculated as follows:

$$\bar{Z}_{th} = \frac{\bar{Z}_T}{2} + \frac{1}{\frac{1}{\bar{Z}_{sh}} + \frac{1}{\bar{Z}_T/2 + \bar{Z}_g}} \quad (11.6)$$

This second Thevenin equivalent comprises of the impedance from equation (11.6) together with the corresponding feeding voltage and the load impedance from above. With this very simple model stability analysis can be performed analytically in a straightforward way. However, practical corridors usually comprise of several lines not always connected to the same sending and receiving node. In this case a reduced network model must be calculated.

Consider the example network diagram in Figure 11.5. To apply the network reduction procedure, first the main load and generation centers must be identified. In this case, a distinct generation center can be found in the area above cut 1, which contains three major generators and some shunt compensation but only a few minor loads. Between cuts 1 and 2 is an area with no generation equipment and only a few minor loads. This is the transmission corridor, whose stability is of interest. In the equivalencing procedure described above, these loads will be implicitly included in the shunt impedance. Below cut 2 is an area with predominantly load character. There are some minor generators, but in cases where the voltage stability is endangered, these generators would have exceeded their capability limits and thus no longer contribute to stabilization. It is therefore reasonable to include them in the shunt impedance modeling of the load.

After identifying the region boundaries, which are given by the two transfer cuts we can define two virtual buses, one for each end of the transmission corridor. These are the buses directly adjacent to a cut. Buses 6, 13 and 14 of the original system are grouped into virtual bus 1, and buses 24, 15 and 16 into virtual bus 2. The part of the system between cuts 1 and 2 becomes the virtual transmission corridor. At least one complex voltage in the area of each virtual bus and the complex currents on each line crossing a cut must be measured by PMUs.

We can then compute the currents at either end of the virtual transmission corridor using:

$$\bar{i}_i = \left(\frac{p_{cut,i} + jq_{cut,i}}{\bar{v}_i} \right)^* \quad i \in 1, 2 \quad (11.7)$$

Here $p_{cut,i}$ and $q_{cut,i}$ refer to the sum of the power transfers through cut i , and $\bar{v}_i$ as the average of the voltages included in virtual bus i .

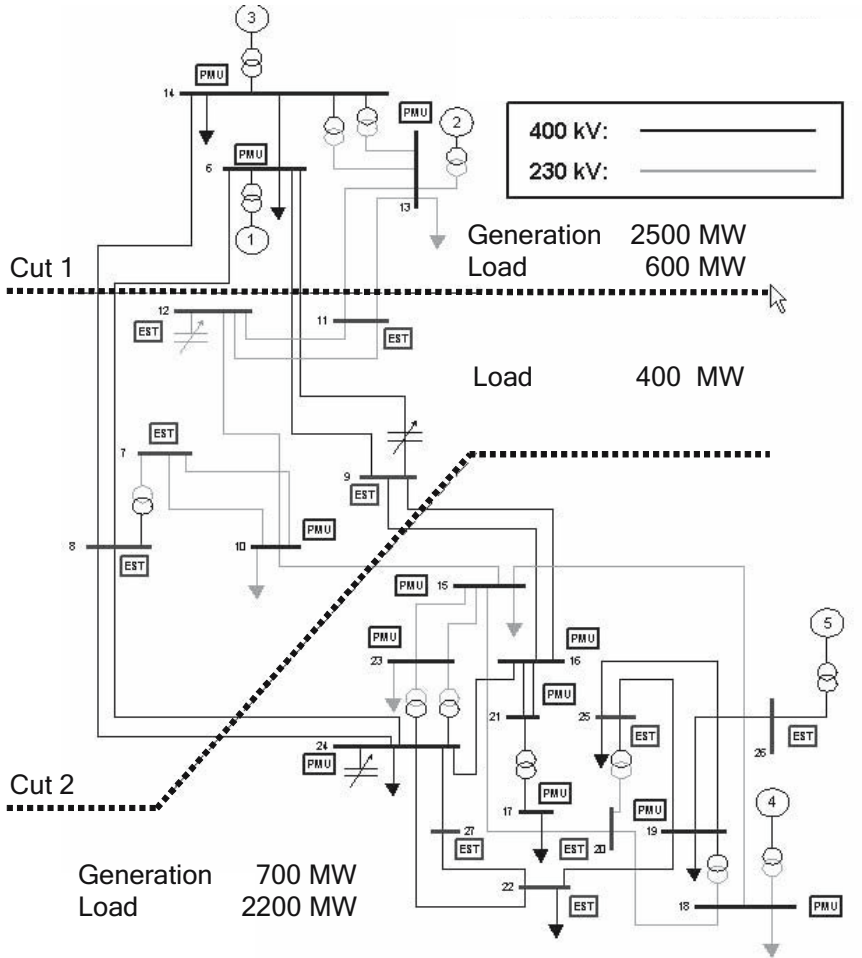


Fig. 11.5. Diagram of a real power system with a corridor situation

Computations of stability margins have to be carried out based on this virtual transmission corridor model. The stability analysis can be performed analytically with the second Thevenin equivalent. The point of maximum power transfer $p_{L\max}$ can be calculated for an assumed load increase with constant power factor.

$$p_{L\max} = \Re \left[\bar{Z}_{th} \left| \frac{\bar{E}_{th}}{2\bar{Z}_{th}} \right|^2 \right] \quad (11.8)$$

Normally at least a part of the load has constant power characteristics, and the point of maximum power transfer as given by equation (11.8) then also becomes a

loadability limit. Past this limit there is a loss of equilibrium and a voltage collapse will occur. Therefore it becomes a stability limit.

11.2.2 Thermal Limit Monitoring

The determination of the average line temperature based on phasor information is quite simple. Starting with the PI-equivalent of the line in Figure 11.6, the line parameters R , X_L , X_C are determined from the voltage and current phasors $\bar{v}_1$, $\bar{i}_1$, $\bar{v}_2$ and $\bar{i}_2$, whereas the resistance R has the largest variability. The changes of inductance and capacitance are small during operation. As an example, the change of the line resistance ΔR of 10 % leads to a loadability change of $\Delta s_{\max} = 6.5$ % for a typical 400-kV-line.

If the actual value of R is determined, the actual line temperature can be calculated according to the following formula:

$$\frac{R_1}{R_2} = \frac{T_1 + T_0}{T_2 + T_0} \quad (11.9)$$

R_1 is the calculated value of R from the phasor measurements. R_2 and T_2 are a pair of values, which are given from the original design of the line. T_0 in eq. (1) is a material constant for the line wires. (e.g. $T_0 = 228$ °C for aluminum). With the given values, the temperature T_1 can be calculated.

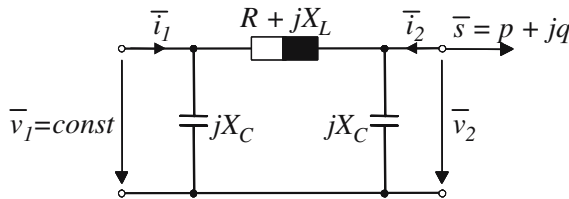


Fig. 11.6. PI-equivalent of a power transmission line

This calculated temperature is the average temperature of the entire line between the two measurement points. This temperature includes the actual situation of ambient conditions like wind speed, sun and line current. Consequently, these data offer much more information than the line current as a loadability limit only. The drawback is that this kind of information cannot identify hot spots and therefore sometimes not replace local temperature measurements.

11.2.3 Oscillatory Stability Monitoring

Initiated by the normal small changes in the system load and disturbances such as generator or line trips, oscillations are characteristics of a power system. However, a small load increase in a line flow, for instance a couple of MWs, may make the difference between stable oscillations, which are acceptable, and unstable oscillations.

tions, which have the potential to cause a system collapse. It is another matter of fact that increasing long-distance power transfers cause the inter-area modes to become lightly damped or even unstable. FACTS-devices like the TCSC are damping these oscillations. However, there is even no warning to the transmission operator so far, if a new operating condition causes an unstable oscillation or not and if the controller works well.

The objective has been to develop an algorithm for a real-time monitoring of oscillations from on-line measured signals; in other words, to estimate the parameters characterizing the electromechanical oscillations such as frequency and damping, and to present this information to the operator in a user-friendly environment of the operator station [5]. This kind of information can hardly be obtained only by watching the measured signals displayed in the time-domain. The on-line collected measured data from the WAMS are subject to a further evaluation with the objective to estimate dominant frequency and damping of the electro-mechanical oscillatory modes during normal operation of the power system. The power system is assumed being driven by small disturbances around a nominal operating point. Methods considered here are parametric, model-based ones. Evaluation of the estimated model parameters enables quantitative detection of oscillations and other properties of the system, such as actual system stability. Moreover, similar models obtained using the same identification techniques may be used for a stabilizing controller design or controller adaptation according to the autonomous scheme introduced in chapter 9. Taking into account the trade-off between model complexity and suitability to represent narrow spectra, linear autoregressive models have been focused on.

The basic scheme is outlined in Figure 11.7. The power system is assumed being driven by white noise disturbances $e(k)$ around a nominal operating point. The system is modeled by a linear autoregressive model with adjustable time-varying coefficients. The system outputs $y(k)$ are the measurements provided by PMUs. The ever-present measurement error is represented by $d(k)$.

An adaptive Kalman filter is used to evaluate the parameters of a reduced-order linear equivalent dynamic model of the power system based on a selection of the measurement inputs. Later the damping and frequency of the dominant modes are extracted through eigenvalue analysis of the equivalent model.

The model-based estimation method chosen here is based on an auto-regressive (AR) model with adjustable time-varying coefficients

$$y(k) = \sum_{i=1}^n a_i y(k-i) - \varepsilon(k) \quad (11.10)$$

with ε given by

$$\varepsilon(k) = \hat{y}(k|k-1) - y(k) \quad (11.11)$$

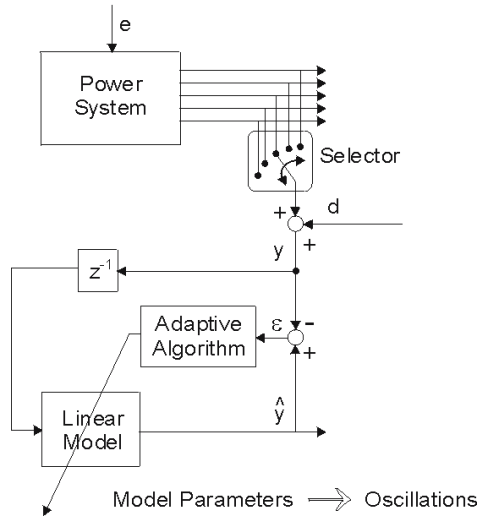


Fig. 11.7. Basic scheme for the proposed detection of power system oscillations

The measured signal y may contain some measurement noise d . An adaptive algorithm recursively optimizes the criterion (11.12) and yields the optimal parameters of the AR-model, generating possibly the same sequence of data $\hat{y}$ as the measured y . The goal is to obtain the parameters of oscillations characterized by their frequency f_i and damping ξ_i . They are obtained repeatedly once per given period with the so called refresh time T , from the AR-model for the set of its n parameters $a_i(k)$. The refresh time defines how often the dominant oscillations are to be calculated from the estimated model parameters and displayed to the operator. This is a trade-off between the computational power of the computer on which the application is running, taking also into account how rapidly the power system varies with time.

Therefore, the first step of the presented approach is to estimate recursively these coefficients $a_i(k)$ that minimize the sum of squared prediction errors

$$J = \min_{a_i} \sum \varepsilon^T \varepsilon = \min_{a_i} \sum (y(k|k-1) - y(k))^2 \quad (11.12)$$

where $\hat{y}(k|k-1)$ denotes the prediction value of $y(k)$ for measurements given up to time $(k-1)$. Recall that the poles of this model contain the required information about the time-varying system dynamics, which depends on the operating point of the power system. The poles can be calculated solving the characteristic equation (11.13) for a set of actual values of $a_i(k)$ frozen at time k .

$$z^n - a_1 z^{n-1} \dots - a_{n-1} z - a_n = 0 \quad (11.13)$$

The assumption here is that the power system is operated at the same operating point for a certain period of time that enables the estimated coefficients to con-

verge. Indeed, this is no constraint in practice since the estimated model parameters converge to their new values fast enough compared to the dynamics of the power system, if e.g. the algorithm proposed here is employed.

For our purpose - estimation of the damping and frequency of the dominant oscillations - the most suitable conversion of the estimated discrete-time model to a continuous-time model is the Tustin's approximation. This one has the advantage of mapping the left half-s-plane into the unit-disc in z-plane and vice versa [6]. Hence, stable discrete-time systems are transferred into stable continuous-time systems whose eigenvalues are then the basis of calculation of the parameters of oscillations. The relationship between z and s to obtain continuous-time poles resp. eigenvalues $\lambda_i = \alpha_i = i\omega_i$ is for the Tustin's approximation given by:

$$z = \frac{1 + sT_s/2}{1 - sT_s/2} \quad (11.14)$$

A normal operating power system is stable. This means $\alpha_i < 0$ for all $i=1\dots n$. Oscillations are characterized by complex eigenvalues. The real part α_i gives the information about the decay rate and the imaginary part

$$\omega_i = 2\pi f_i \quad (11.15)$$

about the frequency f_i [Hz] of the oscillatory mode. A practical measure for damping is the relative damping:

$$\xi_i = 100 \frac{-\alpha_i}{\sqrt{\alpha_i^2 + \omega_i^2}} \% \quad (11.16)$$

It has turned out that the adaptive Kalman filtering technique [7] is an appropriate tool to identify the optimal model parameters. This approach has shown the smallest prediction error and the shortest estimation time; i.e. the number of iterations necessary for the parameters to converge. At the same time, applying this method to different measured signals, the results were not very sensitive with regard to the set of the tuning parameters. The standard set of recursive equations to be solved on-line is for the Kalman filter known to be (11.17), see e.g. [7].

$$\begin{aligned} g(k) &= \frac{K(k-1)u(k)}{u^T(k)K(k-1)u(k) + Q_m} \\ \varepsilon(k) &= u^T(k)p(k-1) - y(k) \\ p(k) &= p(k-1) + \varepsilon(k)g(k) \\ K(k) &= K(k-1) - g(k)u^T(k)K(k-1) + Q_p \end{aligned} \quad (11.17)$$

To ensure good numerical robustness of the standard estimation algorithm, the equations (11.17) have been extended by some additional ones (11.18). The covariance matrix $K(k)$ is enforced here to remain symmetrical, and for a better parameter tracking, a regularized constant trace algorithm is used with $c_1/c_2 \approx 10^4$.

$$K(k) = \frac{K(k) + K^T(k)}{2} \quad (11.18)$$

$$K(k) = \frac{c_1 K(k)}{\text{tr}(K(k))} + c_2 Q_p$$

All the variables can be initialized with zeros, except for the covariance matrix $K(0)$, which should be initialized with a unity matrix multiplied by a large constant. The most important parameter for tuning is the model order n . Its selection is one of the most important aspects for the use of AR models. If one selects a model with too low order, the obtained spectrum will be highly smoothed. On the other hand, if the order is too high, faked low-level peaks in the spectrum will be introduced. The measured signal $y(k)$ is filtered through a digital band-pass filter (with the cut-off frequencies 0.1Hz and 2Hz).

Besides the described real-time estimation of frequency and damping, the running mean value and the amplitude of oscillations can be calculated. This is performed by two self-tuning digital low-pass filters placed before and after the input band-pass filtering. The time constants of these two filters are simply taken over from the estimated dominant frequency.

To show the performance of the algorithm it has been applied to real measurement data from existing WAMS installations. Figure 11.8 shows an example which contains a drastically change in the system structure during the measurement period.

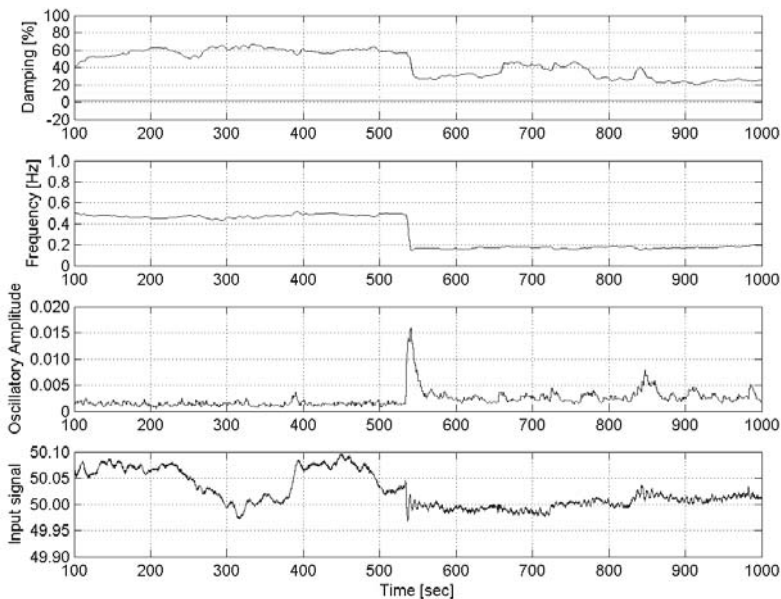


Fig. 11.8. Oscillation detection algorithm applied to real PMU measurement data

On the left hand side the system has well damped oscillatory modes and only variations by very slow control actions. After the change in the system structure at 530 s the dominant frequency is going down to 0.2 Hz with a reduced damping. The situation is still uncritical. The provision of this information to the operator during the switching in the system made them feel much more comfortable, because of the better observability.

11.2.4 Topology Detection and State Calculation

When enough measurements are available, it is possible to completely detect the status of each network element and to calculate each voltage and current of the network. Topology detection and state calculation is used to provide snapshots of the power system 10-20 times per second. The present topology of the network is inferred from the raw PMU measurements, and therefore the WAMS does not rely on other sources, such a SCADA system for topology information. Therefore the data rate of the PMU can be followed without time delays implied by other sources. The basic function is that the PMU measurement directly shows if a line or another network element is in service or switched off. With several measurements in a region a selection of assumed topology can be verified to fit to the actual one. Another part of the topology detection is an islanding identification to detect if the system has separated into smaller areas.

The next step after the topology analysis is the state-calculation, which is executed once for each island, and serves the purpose of computing the voltages and currents at each bus in the island, also those where no PMUs have been installed.

The classical iterative state estimation, which primarily serves to identify measurement errors, can be represented by the non-linear measurement model in equation (11.19).

$$\underline{z} = \underline{h}(\underline{x}) + \underline{v} \quad (11.19)$$

The states $\underline{x}$ are complex bus voltages, with magnitude and phase angle. Traditionally, phase angles could not be measured due to impossibility to handle the synchronization of measurement devices. The classical state estimation derives these values from other measurements, such as voltage magnitudes or line active and reactive power flows and eliminated measurement errors $\underline{v}$.

The basic problems of the state estimation are coming from several sources. The network parameters are changing over time with ambient conditions (e.g. temperature, radiation, aging of devices etc.). The topology of the network needs to be updated automatically or manually dependent on the switching status of the devices (line in or out e.g. for service or after a fault). If the topology is not maintained carefully in the system, the state estimation results are wrong. Furthermore the state estimation assumes that the system is in a steady-state situation. In transient situations e.g. after a series of faults, the topology status and the measurement values are not necessarily fitting together which gives bad results for the state estimation. In fringe areas of a power system the redundancy of measure-

ments is usually not given or weak. This means that the state estimation is not able to compensate either bad measurement values or inaccuracies in network parameters.

These drawbacks to the classical state estimation can be eliminated by a WAMS based one. A PMU based state is introduced in [8][9]. If only PMUs are used, the angles of voltage and currents are directly measured. The measurement model in this case is linear according to (11.20).

$$\underline{z} = \underline{H} \cdot \underline{x} + \underline{v} \quad (11.20)$$

In this case the influence of the network parameters remains until PMUs are used to determine as well the actual parameters like in the thermal line monitoring algorithm in section 11.2.2. Due to the linearity of the equation, the PMU based state-estimation is a non-iterative process and therefore a solution in predictable time can be guaranteed.

Setting up a PMU based state estimation to the system in Figure 11.5 leads to a selected number of buses with PMU from which the missing network states can be determined. The figure shows the buses where the PMUs have been placed (marked PMU) and where voltages and currents are estimated (marked EST).

11.2.5 Loadability Calculation based on OPF Techniques

A detailed voltage stability assessment can be made based on the network model and state information that is received from the state- and topology calculation. Based on the network and state information, a load increase can be simulated on a number of selected buses until the point of maximum loadability is reached. The procedure employs nonlinear optimization techniques to compute the maximum transfer capacity for the topology with which the power system is currently operating but also for various contingency scenarios. Such techniques have been proposed for off-line application for example by [10], but similar ideas can be applied to on-line applications. In mathematical terms the general formulation is:

$$\begin{aligned} &\text{maximise} && f(p, x) \\ &\text{subject to} && g(p, x) = 0 \\ &&& h(p, x) \leq 0 \end{aligned} \quad (11.21)$$

The function to maximize $f(p, x)$ can be arbitrarily chosen based on the criteria to be optimized. In this case it is chosen as a fictitious active power transfer to a set of load buses known *a-priori* to be critical for the voltage stability or the transfer to a predefined critical area or through a corridor. The optimization variable p can be scalar or vector valued and is the parameter that is varied to simulate a load increase. The function $g(p, x)$ represents the constraints given by the network equations as well as the steady state response of the FACTS-control systems and other controllers. The function $h(p, x)$ contains various operational constraints such as voltage or current limits and actuator limits of the FACTS-devices. The vector x contains the (static) state variables of the network equations, and are implicitly determined by the equality constraints.

From the solution of (11.21), the maximum allowable transfer to the region can be computed and a power margin taken as the difference between the maximum transfer and the transfer at the current operating point.

Before the calculation an admittance matrix is constructed based on the snapshot from the wide-area measurement system. This admittance matrix is required to evaluate the function $g(p, x)$. If desired, N-1 contingency screening can be done by repeatedly solving (11.21). Different contingencies are modeled by modifying the admittance matrix in case of simulated line trips or by changing the load-flow input data in case of generator trips, prior to the solution of (11.21). In this optimization method the setpoints of FACTS-devices can be included as variables. More details on that will be shown in a later section 11.3.

The drawback of this method is the high demand of on-line data and measurements. It requires a WAMS installation with full observability which means both state and topology estimation, and consequently a relatively large number of PMUs. The advantage is that accurate power margins can be calculated and optimal setpoints can be generated. This method is also applicable for general network topologies.

11.2.6 Voltage Stability Prediction

For the problem of emergency voltage stability control the two phenomena of short and long term voltage instability must be addressed. If a system is in normal operation, only cascaded or combined outages lead to instability. In most of the practical system collapses long term unfolding instabilities occurred. The reason is that after the initial contingencies the weak situation was not detected well, following events were not foreseen and no appropriate remedial actions were taken. Therefore, either long-term voltage instability or a following event caused by protection mismatch occurred. In both cases the complexity of the problem is beyond that can be foreseen with pre-calculations on N-x base. Therefore any algorithm must be triggered and run after the first events.

After a contingency occurs, the system is in a dynamic phase, which is in the case of long-term voltage instability determined by control actions for instance from tap changers (ULTC), overload capacity of generators and load recovery [11][12]. This characteristic leads to a retarded behaviour, which may lead to a collapse. The idea is to predict just after an event if a collapse might occur.

After a contingency, a sliding data window of PMU measurements is used to determine the actual system and especially load characteristic. A dynamic model is fed with this information. The equilibrium of this model is determined without a time domain simulation. If there is an equilibrium, the system is predicted to be stable, otherwise the system will collapse. Figure 11.9 shows the principle of this approach. Phase 1 is the normal operation where N-1 calculations can be performed. Phase 2 is stable under the assumption that phase 1 was N-1 stable. After the second contingency it is not obvious at the beginning if the system is stable or not.

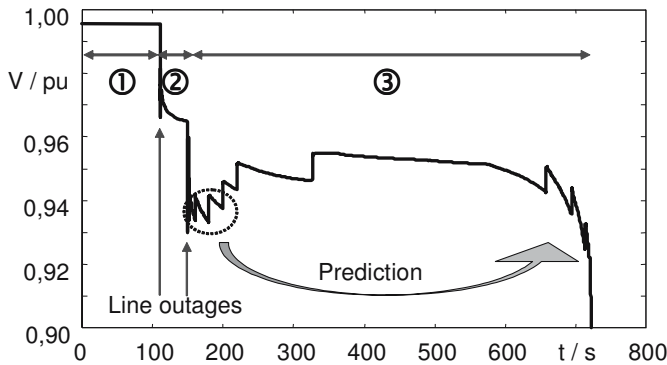


Fig. 11.9. Simulated voltage collapse of the power system in Figure 11.5

From the conventional viewpoint of the operator, the voltage is coming back and the system seems to be stabilized during the phase 3 of the simulation. But the underlying dynamics lead the system finally into a collapse. The information from the prediction algorithm can also be used for the determination of stabilising actions.

The steady state equilibrium of the full dynamic system model (11.22) is determined using a model reduction. G are the power flow equations and z the bus voltage magnitudes and angles. F are the remaining equations and x the remaining state variables.

$$\begin{aligned}\dot{x} &= F(x, z) \\ 0 &= G(x, z)\end{aligned}\quad (11.22)$$

At first, all short-term transients in the model are neglected. ULTC, voltage controllers, reactive power limiters and load characteristics can be approximated by their steady-state behavior. To find the equilibrium of the remaining equation system (11.23) a Newton-Raphson algorithm is applied. In (11.23) F_s are the simplified equations with the reduced state vector x_s .

$$\begin{aligned}0 &= F_s(x_s, z) \\ 0 &= G(x_s, z)\end{aligned}\quad (11.18)$$

With this model simplification the transient characteristics are separated from the interesting steady-state ones.

To set up the full algorithm the following steps has to be performed. While the system is running in a steady-state situation, the steady-state values of bus voltages V_0 and load powers P_0 and Q_0 must be traced and contingencies such as changes in the topology must be detected. After a contingency is detected the parameters of an applied load model, which describes the voltage dependency of the power, must be determined.

A general load model is shown in (11.24). P_0 and V_0 are the base power and voltage before the contingency and $\dot{P}$ and $\dot{V}$ are the power and voltage gradients at a certain time step t . $\mathbf{p}$ is a vector containing all unknown load parameters.

$$P(t) = f(P_0, V_0, \dot{P}(t), \dot{V}(t), V(t), \mathbf{p}) \quad (11.24)$$

An example of a typical load model is the Hill and Karlsson model in (11.25), which shows the typical load recovery characteristic after voltage steps [13]. But also any other model, like e.g. composite ones, can be used.

$$P = -T_p \dot{P} + P_0 \left(\frac{V}{V_0} \right)^{\alpha_s} + \frac{P_0}{V_0} \dot{V} T_p \alpha_t \left(\frac{V}{V_0} \right)^{\alpha_t - 1} \quad (11.25)$$

To determine the load parameters, a sliding window of voltages V at each bus and feeder loads P , Q are collected. $\dot{P}$ and $\dot{V}$ are the mean values of the gradients between two timely neighboring measurement points. A set of load equations (11.24) for different time steps within this window builds a nonlinear equation system, which has to be solved for the unknown parameters $\mathbf{p}$. This equation system can be solved with a non-linear solver algorithm (e.g. Nelder-Mead). When the number of equations is greater than the load parameters the equation system is over-determined, which increases the accuracy and robustness of the results. Alternatively, a simplified linear solving algorithm is proposed in [14].

The algorithm must be calculated for each relevant load in the system. If it can be seen that the loads behave similarly in a certain area of the system, the number of calculations can be reduced to single examples for each area.

The determined load parameters are fed into the simplified system model to be solved for the equilibrium as described above. This equilibrium point is the predicted state of the system, which might be tens of seconds in the future. If no equilibrium is found, the transient phase will end in a collapse. In both cases a positive or negative power margin can be determined with a continuation power flow [15][16] or optimization technique from the previous section.

Figure 11.10 shows the loadability as a power margin PM for the predicted and the non-predicted case for the power system from Figure 11.5 after two contingencies, which are not leading to a collapse. The sensitivity after the first contingency is still low. Therefore the effect of the prediction is also low. After the second contingency the system is operating in a more sensitive resp. non-linear operational point showing a more significant difference between the algorithm with and without prediction. From the beginning of the prediction after the second contingency it needs about 50 s until the non-predicted power margin PM is the same as the predicted one. Therefore the forecast of the proposed algorithm is about 50 s in this example. As a result, the criticality of the system will be predicted earlier and also remedial actions can be taken without delay.

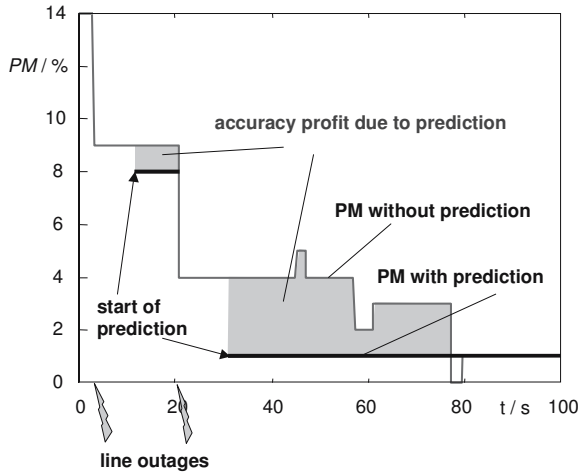


Fig. 11.10. Power Margin calculated with and without prediction during two contingencies in the power system in Figure 11.5

11.3 Wide Area Control Applications

As shown in the previous chapters a significant added value of FACTS-devices can be gained by introducing secondary control that coordinates the setpoints of FACTS-controllers. In particular contingency cases are important, since they can have dramatic influence on the network flows. The speed and continuous control capability of FACTS-devices make these devices especially useful for improving transfer capacity in these contingency cases, since they can adapt to new flow situations much faster than traditional devices.

All the algorithms in the previous section serve as the basic information to identify critical system situations and instabilities. The algorithms are designed based on the PMU information and therefore provide the information dynamically and in very short time intervals. Both are mandatory to use the speed of the FACTS-devices. This section introduces a selection of algorithms and examples using the basic monitoring methods and apply them in FACTS control schemes. The criteria from the NISC architecture in chapter 9 and the autonomous system in chapter 10 are considered.

In the following a general method based on full network supervision is introduced. This method is a predictive voltage stability control with FACTS setpoint determination using optimization techniques. A simplified method based on limited PMU information can be derived from this first one. A coordination of FACTS control is achieved by using feedback from selected remote PMU measurements. This method enhance transmission capacity restricted for instance by voltage stability in well defined network situations, for instance like corridors.

11.3.1 Predictive Control with Setpoint Optimization

Setpoints for the FACTS-devices have to be determined in three basic cases. The first one is the optimization of an actual operational situation. This is equal to the classic Optimized Power Flow (OPF). A second application is the pre-contingency calculation to be prepared for the next event, according to the autonomous system approach in chapter 10. The system has to determine set values for a selection of critical contingencies which might occur. The third application is the post-contingency case, where either directly or after executing the prediction algorithm of section 11.2.6 an optimal set of FACTS setpoints has to be determined.

By a slight modification of equation (11.21) in section 11.2.5 we can extend the method so that it also generates optimal setpoints for FACTS-devices. The resulting setpoints are optimal in the sense that they maximize the loadability criterion $f(p, x, u)$. Now, a vector of the FACTS-device setpoints (u) is included together with p as optimization variables. The modified optimization problem becomes:

$$\begin{aligned} &\text{maximise} && f(p, x, u) \\ &\text{subject to} && g(p, x, u) = 0 \\ &&& h(p, x, u) \leq 0 \end{aligned} \tag{11.26}$$

The solution of (11.26) yields the optimal FACTS setpoints as well as the maximum loadability when these setpoints are applied. If the contingency screening is applied using this method, also FACTS setpoints that maximize the loadability can be pre-computed for a list of credible disturbances. Based on this method the real corridor situation of Figure 11.5 is discussed in the following.

For power transfer capability increase, shunt connected devices such as SVCs have been proven cost-effective, especially when fast or continuously controllable compensation is necessary due to stability or voltage quality concerns. Typically, an SVC also has a voltage controller that controls the terminal voltage so that it is close to a (fixed) reference value. To control power flow, series connected devices such as phase-shifting transformer, TCSC or DFC can be used.

The controllers that are typically embedded in the FACTS-devices are here referred to as primary controllers, and are typically of P- or PI- type, with special supplementary controllers like damping controllers. Normally, the setpoints for FACTS-devices are kept constant or changed manually on a slow timescale based on market activities or optimal power-flow calculations for the base case. Typical FACTS-device controllers operate purely based on local criteria with the objective to control a single local quantity such as voltage or power-flow. The performance objectives of the controllers do not consider their effect on the power system as a whole.

The optimization basically introduces a secondary control loop that generates the setpoints for the primary FACTS-controllers as discussed in the autonomous system in chapter 10. Additionally to the basic rules in the autonomous system the optimization algorithm provides concrete numbers for the set value adaptation, which have to be pre-calculated. The approach avoids the conflict of the secondary control with the objectives of the local primary control loops. For example, using a power-flow control device to reduce power flow to a load area can jeop-

ardize system stability since it would introduce additional (apparent) reactance which could cause or contribute to voltage instability. When the system is operating close to or possibly even beyond stability limits, it would be wise to relax the primary control objectives in favor of the objective to improve stability margins. The task of the secondary controllers is thus to detect when stability margins are small and to carry out appropriate setpoint corrections to improve stability margins.

Figure 11.11 shows the results of a loadability analysis and secondary control actions of the system in Figure 11.5 for the base case and different contingency cases. The system has three FACTS-devices, one Power Flow Control Device (PFD) between bus 6 and 9 and two SVCs at buses 12 and 24. Usually the SVCs would try to keep the voltage according to their reference value independent from the corridor situation. Since one of the aims is to demonstrate the benefits of wide-area FACTS-control, the analysis is made three times. Once with the FACTS-devices deactivated, and once with the FACTS-devices using traditional local controllers and once with the FACTS-devices using the optimal setpoints to maximize transfer capability to the load region. The dashed line illustrates the actual loading, and the bars the maximum possible loading for a particular contingency and with a particular configuration of the FACTS-devices. One observation that can be made in the figure is that the added capacity by coordinated optimal FACTS-control can stabilize a system that would otherwise be unstable as in the case for contingency number 1 in the Figure 11.11.

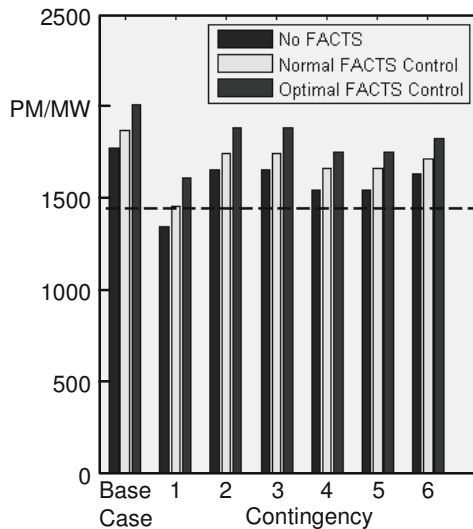


Fig. 11.11. Loadability analysis of the power system from Figure 11.5 showing the power margin (PM) for base case and contingency cases

For the shown contingency cases the set-values are pre-calculated. New predefined actions have to be determined continuously according to slightly changing operational conditions and especially after a contingency to be prepared for at least the following one like described in chapter 10. If there is no time to perform the pre-calculation because of multiple contingencies, a post calculation approach has to be applied like the prediction method in section 11.2.6.

But if the contingency is more severe and there is not time to perform the prediction, which means that the system for instance suffers a short-term voltage instability, either predefined actions on a system base or conventional protections like under-voltage protection schemes have to act. In conclusion the control scheme is as follows:

- Steady state or predicted stable operation: The set-values follow the continuous change of the system operation. Predefined actions are determined continuously to act after next contingency
- One contingency occurs (long-term instability): If available and necessary, predefined actions are taken. The prediction process is started and stabilising actions are taken or predefined for next contingency.
- Cascaded contingencies occur (long-term instability): The prediction process is started and stabilising actions are taken or predefined for next contingency.
- Short-term instability: Either predefined system wide actions are taken or conventional protection schemes are acting.

11.3.2 Remote Feedback Control

Instead of using full system observability like in the previous section, the remote feedback control schemes use selected remote measurements to detect stability problems in a power system and to determine adapted FACTS setpoints. For simple network topologies, guidelines for the design of feedback controllers to coordinate multiple FACTS-devices can be described. The main advantage of these schemes is that they are simple to implement and stand-alone, but they must be customized for each particular network.

This approach is applicable when the system situation is simple enough and the problems which might occur are limited in number and are well predictable. The remote feedback controller can be derived from a rule base defining a set of actions to be taken in a number of situations. Therefore this kind of control is part of the autonomous system description in chapter 10.

For the situation in Figure 11.5 a remote feedback controller can be designed. The Power Flow Control Device (PFD) has a nominal setpoint for the active power transfer equal to the power transfer through the line before the device is activated. However, as disturbances are applied or the load level changes, the PFD will keep the power transfer through itself close to the reference value until it has saturated. Applying this control the PFD is limiting the maximum transfer over the corridor, because it is not coordinated with the SVCs. It even may reduce the benefits of the SVCs. This is due to the detrimental behavior of the PFD, which

introduces additional reactance to reduce the flow through line 6–9 when the load in the southern area is increased. Applying the optimal control, however makes it possible to use the PFD to its full potential to increase transfer capacity. The transfer capacity increase becomes significant about 11 % over the corridor. The capacity increase is achieved through a setpoint adaptation for the PFD as well as the SVC at bus 12.

Figure 11.12 shows how a secondary control loop based on feedback control can be used to achieve near-optimal control. This new secondary loop uses the voltage of bus 24 as feedback signal and operates on the PFD power reference. The PFD secondary loop is using a PI controller with deadband ± 0.08 pu, output limits of ± 4 pu, the gain $K_r = 100$ and the rise time $T_r = 1$ s.

Figure 11.13 shows the PV-curves obtained through dynamic simulation of the system with the PFD and two SVCs. The three curves show results with FACTS-devices disabled, with the FACTS-devices using conventional local controllers and with the feedback based secondary control scheme.

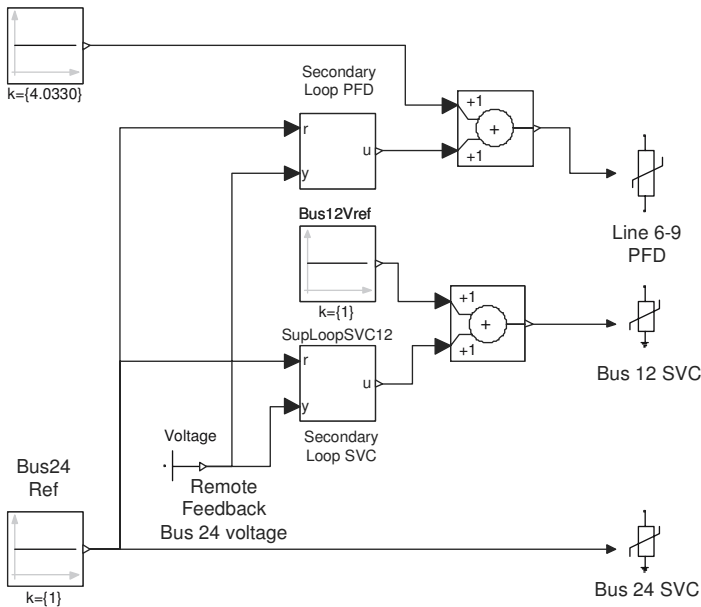


Fig. 11.12. Secondary control loop for two SVCs and one power flow control device (PFD)

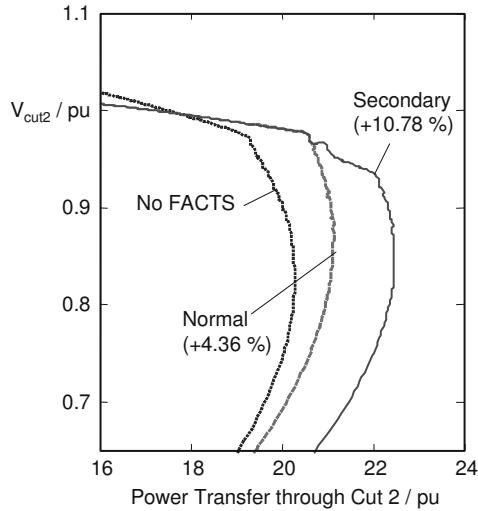


Fig. 11.13. PV curves for the system in Figure 11.5 without FACTS, for conventional local FACTS control (normal) and a secondary control scheme

In a second case study it will be shown how wide-area control can be used also in the case of active power flow control when the network topology is more complex than a simple radial corridor as in the first case study. The case design has been inspired by a collapse situation in the central part of the European interconnected network represented by a simplified system in Figure 11.14. The wide-area control scheme is designed only from the point of view of one area (Area 2). It is clear however, that the best solution for the system as a whole would be a global controller for all FACTS-devices in the system. However, since different TSO's operate the system, it would not be easy to implement such a control scheme because of organizational reasons. We therefore consider only regional wide-area controls.

The scheme here has been designed to avoid corridor overloads and not to maximize NTC (loadability) as in the other case. For a control system with this complexity, the optimization based scheme from the previous section 11.3.1 could also be considered, but a remote feedback control based on pre-defined rules is applicable as well.

The corridor between Area 1 and Area 2 (L1) has a transfer limit of 1.2 pu (on a 1000 MVA base). The corridor between Area 1 and Area 4 (L2) normally has a higher transfer limit, but after a line trip the transfer limit will be decreased to about 1 pu. This corridor is equipped with a phase shifting transformer (T1) equipped with a local power-flow control loop. The low voltage part of the corridor within Area 2 (L5) has a transfer limit of 0.65 pu. This corridor is actually composed of many parallel lines and cannot easily be equipped with compensation or power flow controllers. Area 1 is primarily an exporting area, Area 2 is import-export neutral, Area 3 is exporting and Area 4 is an importing area.

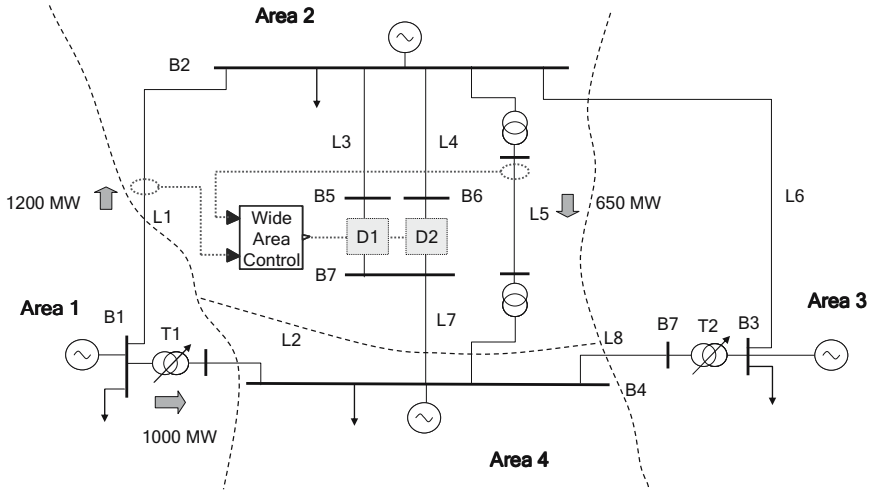


Fig. 11.14. Four area system representing a part of the European interconnected network. Transfer limits are marked with block arrows. Power Flow Controller Devices D1 and D2 with Wide Area Control Scheme.

For a first scenario the elements D1 and D2 are neglected. A critical scenario for this configuration is that corridor L2 experiences a line trip which decreases the transfer limit to 1 pu. Therefore, the active power reference value for T1 is reduced to the same value. Figure 11.15 shows the power flows on the corridors following this setpoint decrease.

The flow through corridor L2 decreases to a value close to its reference, however the transformer saturates at its maximum tap step. As the flow decreases through L2, the flow is shifted to the corridor L1 which is overloaded as well as the lines L3 and L4. At this stage the loading of corridor L5 is still below the transfer limit. This case illustrates that the central Area 2 is vulnerable to overload, when the PSTs in Area 1 or Area 3 are used to redirect power-flows away from corridors L2 or L8. This is a natural consequence of Area 2 having the only uncontrolled path leading to the import Area 4.

In order to provide better controllability on the north-south corridor consisting of line L3 and L4, which is the main path, power flow control devices are considered for installation in this corridor. We first consider two phase-shifting transformers (PST), identical to T1 installed at the locations D1 and D2. The two new PSTs are using constant active power references. Figure 11.16 shows simulation results for this case. The two new devices successfully keep the flow on corridor L1 well below the limit, but as a consequence more power is forced through the low voltage corridor L5, which is overloaded instead.

The previously described scenario clearly demonstrates that the standard constant power reference controllers for the PSTs at D1 and D2 are too egoistic. They successfully keep the flow at L3 and L4 close to the reference value, but their control leads to overload in the low voltage corridor.

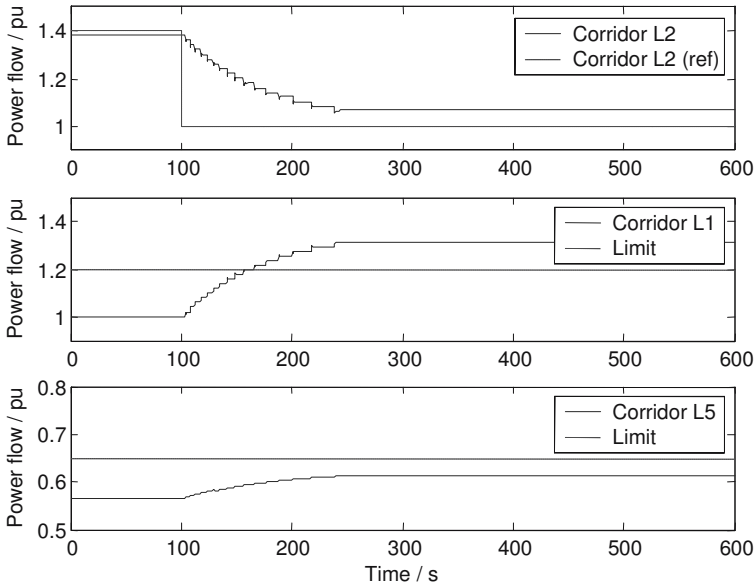


Fig. 11.15. Power transfers in the corridors following reference change to 1 pu for T1

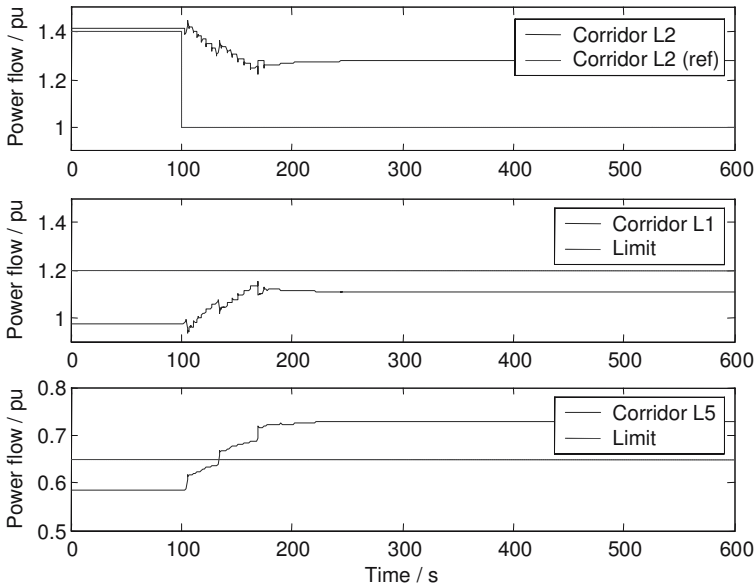


Fig. 11.16. Power transfers in the corridors with PSTs at D1 and D2

In the following, a wide-area controller based on feedback is designed using the power transfer through L1 and L5 as measurements and the power references for D1 and D2 as actuator. The controller has the following priorities as rules for its actions as follows:

- Priority 1 - Avoid overload of low voltage corridor L5 (0.65 pu),
- Priority 2 - Avoid overload of corridor L1 (1.00 pu),
- Priority 3 - Control power flow through L3 and L4 to predefined reference (2.74 pu in this case),
- Alarm operator if the two conflicting Priority 1 and Priority 2 objectives cannot be fulfilled simultaneously.

The first two objectives become conflicting since reducing overload on the lower voltage level comes at the cost of lowering the apparent impedance (using the PSTs) of L3 and L4. This will increase the flow on the uncontrolled L1 corridor. In case of alarm, the operators must request the operators of Area 1 to reduce production until the overload situation in Area 2 is solved.

By inspection of the network topology, we can design the following controller logic that would address the above described objectives:

- In case of overload on L5, increase setpoints for D1 and D2
- In case of overload on L1 and if there is sufficient margin on L5 corridor, decrease power reference for D1 and D2
- If there is an overload on L1 and not sufficient margin on L5 corridor, the operator should be alarmed, so that a request for relieving the corridor by generation reduction in Area 1 can be made.
- If there is no overload on either L1 or L5 keep reference constant on D1 and D2

Figure 11.17 shows the responses to the initial power reference change at L2 when the wide-area controller is used as a secondary controller for the PSTs at D1 and D2. As decided by the prioritization of the objectives, the secondary controller relieves the overload on L5 but allows overload on L1. The benefit is that L3, L4 and L5 are together used to its maximum. Since both overload constraints could not be met simultaneously, an alarm signal is given at about 190 seconds that shows that further actions are necessary to relieve overload. Because of the response time of the PSTs D1 and D2, there is an overshoot in the limit for L5.

In conclusion the wide-area control scheme allows using the installed transmission capacity between Area 2 and 4 to its maximum, independent of what is happening in the areas around. The scheme acts fully automatic and is transparent for the operator. In case of limitations a warning is generated asking for manual interventions. These actions could be included as well in the wide-area scheme requiring setting up the scheme between different TSO operation areas.

The same approach which was discussed here with PSTs can be applied to fast controllable power flow controllers like the Dynamic Flow Controller (DFC) as well. Figure 11.18 shows the respective results for the same scenario.

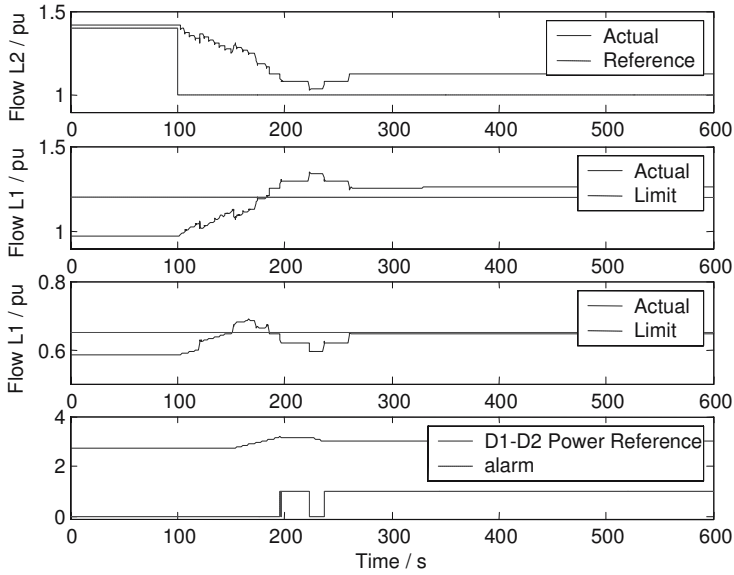


Fig. 11.17. Power transfers in the corridors with secondary control for PSTs at D1 and D2

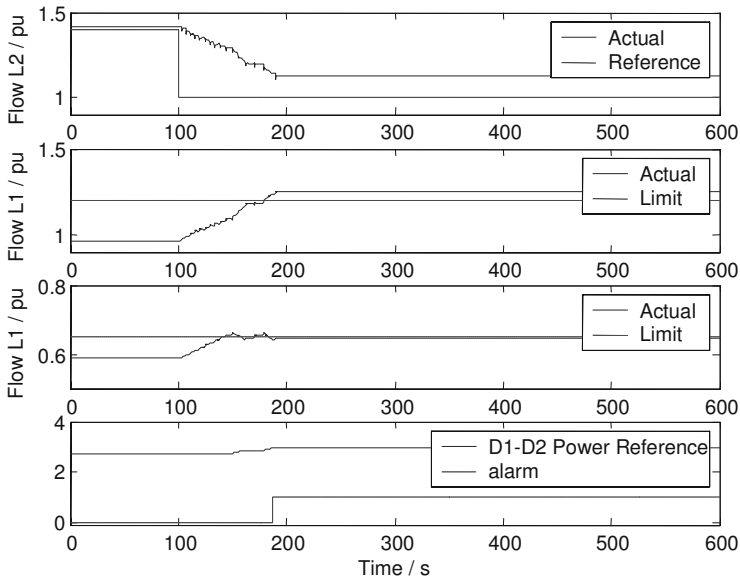


Fig. 11.18. Power transfers in the corridors with secondary control for Dynamic Flow Controllers DFC instead of PSTs at D1 and D2

The approach which was discussed here is fulfilling the requirements of the NISC-architecture in chapter 9. The solution shown is one practical representation of the rule base according to the autonomous system approach from chapter 10. In case of topology changes within the corridor between Area 2 and 4 the rules might be adapted. Other functionalities of the FACTS-devices like damping control or a coordination of the power flow control devices with reactive compensation like SVCs to maximize the transfer capability (see section 11.3.1) can be implemented additionally.

The case studies in this chapter have shown that significant added value of FACTS-devices can be gained by introducing wide-area control that coordinates the setpoints of FACTS-controllers. Only with the consideration of the approaches presented in the chapters 9, 10 and 11 a beneficial use of power flow controlling FACTS-devices can be achieved. Normal operations as well as emergency situations have been considered. The speed and continuous control capability of FACTS-devices make them especially useful for improving transfer capacity in emergency situations, since they can adapt to new flow situations much faster than traditional devices.

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